Development of Bonded Joint Technology for a Rigidizable-Inflatable Deployable Truss

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ABSTRACT

Microwave and Synthetic Aperture Radar antenna systems have been developed as instrument systems using truss structures as their primary support and deployment mechanism for over a decade. NASA Langley Research Center has been investigating fabrication, modular assembly, and deployment methods of lightweight rigidizable/inflatable linear truss structures during that time for large spacecraft systems. The primary goal of the research at Langley Research Center is to advance these existing state-of-the-art joining and deployment concepts to achieve prototype system performance in a relevant space environment. During 2005, the development, fabrication, and testing of a 6.7 meter multi-bay, deployable linear truss was conducted at Langley Research Center to demonstrate functional and precision metrics of a rigidizable/inflatable truss structure.

The present paper is intended to summarize aspects of bonded joint technology developed for the 6.7 meter deployable linear truss structure while providing a brief overview of the entire truss fabrication, assembly, and deployment methodology. A description of the basic joint design, surface preparation investigations, and experimental joint testing of component joint test articles will be described. Specifically, the performance of two room temperature adhesives were investigated to obtain qualitative data related to tube folding testing and quantitative data related to tensile shear strength testing. It was determined from the testing that a polyurethane-based adhesive best met the rigidizable/inflatable truss project requirements.

Keywords: Rigidizable-inflatable, deployable, linear truss, adhesively bonded joints, composite, radar antenna systems

1. INTRODUCTION

The development and validation of an integrated rigidizable/inflatable (RI) truss structure and operational antenna instrument offer performance improvements over existing state-of-the-art deployable truss structures in terms of packaging efficiency and reduced weight, and influence the design of low mass space structures. These key features provided by an integrated RI truss and antenna serve as enabling technologies for multiple space-borne instruments, Figure 1. Specifically, the Vegetation Synthetic Aperture Radar (SAR) requires new technology in order to fabricate lightweight and low-stow-volume antennae, both of which are being addressed during the present research effort. Similarly, the LEO and MEO Interferometric SARs as well as the Geosynchronous Interferometric SAR have sensor requirements that emphasize the need for lightweight, deployable antenna structures.

A number of the NASA Earth-Sun Systems Division (ESSD) science themes have requirements for spatial resolutions of 10 - 100 km for microwave radiometry instruments. Both passive and active (radar) sensors have been designed and tested to monitor various properties of 1) the land surface, including temperature, vegetation, soil moisture, snow depth, and ice thickness, 2) the ocean surface, including temperature and salinity, and 3) the atmosphere, including precipitation, clouds and water vapor. In many situations, the electromagnetic energy emitted from these surfaces is small, especially in the microwave region. Therefore, it is advantageous to have as large a receiving antenna as possible to enable characterization of the target by capturing a sufficient amount of energy, leading to a higher spatial resolution of the geophysical quantity being observed. Current technologies for passive systems only allow rather course spatial resolutions on the order of tens of kilometers. Such large spatial footprints generally involve a wide range of characteristics with different emissivities. Larger antennas that permit higher surface resolutions will allow better

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understanding of the heterogeneity of the earth's surface that can lead to improved modeling and prediction of earth's weather, and climate. The NASA Earth Science Technology Office (ESTO) held a workshop in March of 2003 to define technology requirements for the implementation of NASA's Science Missions in the next decade. Furthermore, this workshop identified Large Deployable Antenna (LDA) radiometer sensor concepts as important to many science applications, e.g. soil moisture, salinity, snow cover, accumulation, and water content. The workshop identified larger deployable concepts at 1.4 GHz as "Required Capabilities" and identified the need for low loss antenna concepts as being a particularly important issue. The technology developed being here is thus a key to enabling the required spatial resolution needed for many Science Directorate missions.

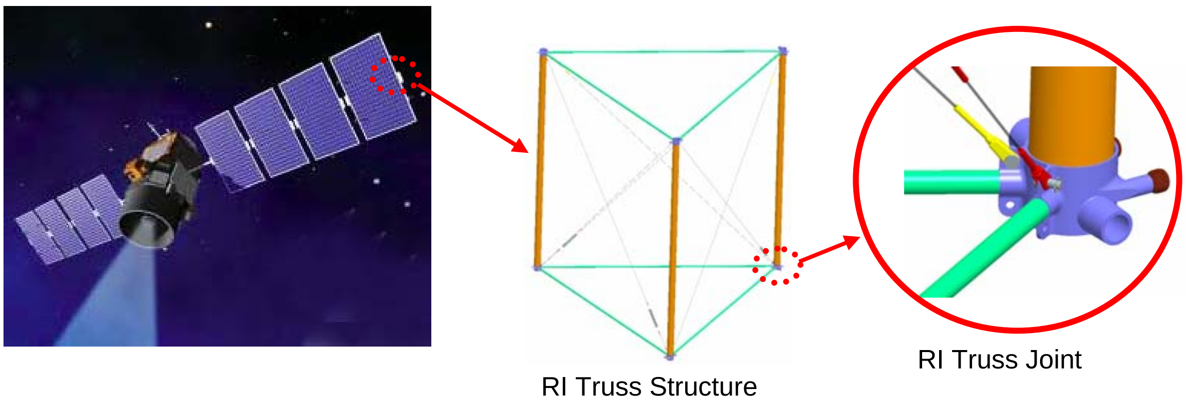


Fig. 1. Examples of RI truss and joint technology as enabling antenna support structure for a proposed synthetic aperture radar antenna.

Linear and planar space-structures developed with RI truss elements have matured significantly during the past ten years[1-5]; however, additional development of the RI truss technology will be required to prepare a flight-ready instrument. Research conducted through the Large Radar Antenna (LRA) program sponsored by the Department of Defense (DOD) and the DARPA sponsored Innovative Space-based Antenna Technology (ISAT) program served to validate critical and enabling technologies related to RI space-structures[6]. Specifically, the orbital radiation durability of RI truss materials and the on-orbit feasibility of high-modulus, RI truss members. Further maturation of the RI technology is needed and would be addressed by successfully advancing two key areas: joining technologies and sub-system integration.

An individual bay of a truss structure, as shown in the center image of Figure 1, is typically joined to other truss bays using small end-joints as shown in the right-most image of Figure 1. In practice, the individual truss bays are designed to be joined to each other in a long chain-like manner that provides sufficient stiffness and stability to operate a number of scientific instruments. However, the structural design requirements for these RI truss end-joints are quite different from those of typical tubular joint assemblies, which in themselves presented quite a design challenge. The majority of research conducted on bonding tubular structures has focused on developing and analyzing tubular joints primarily developed for automotive applications. Of these studies, the primary focus of the investigations has either been on joint strength due to torsional loading[7-9], axial loading[10.11], or the effect of temperature gradients[12] on the joint performance. A few studies have evaluated more generic joint configurations that were useful for determining the effects of combined loads[13,14] on the bonded joint. However, the development of a bonded joint configuration for a RI truss structure requires a different set of requirements than those focused primarily on axial or torsional joint strength. Thus, it is necessary to conduct research to address the different performance requirements of a RI truss and to develop a bonded joint concept applicable to a space regime.

A substantial amount of structural analysis of the current four-bay truss joint has been in previous studies. Basic linear elastic stress analyses were performed of the truss joint to evaluate the strength of a variety of features and their respective margins of safety, but will not be discussed in the present paper in detail. The bond between the end-joint and longeron were evaluated using closed form and semi-analytical bonded joint analysis methods. The bonding test

results presented in the remainder of this paper were primarily conducted to validate the previously described analysis results and identify potential failure mechanisms. The various fittings and lugs on the end-joint were also evaluated using finite element methods (FEM) to determine their response due to the handling and deployment loads identified for the truss structure. These cylindrical features and lugs shown in Figure 2a were not expected to incur high loads; the most severe load case was determined to be loading due to handling of the assembled truss. A contour plot of the von Mises stresses on one of the roller struts is shown in Figure 3 for a load case simulating a handling event. Both the structural bond and the individual features were determined to have adequate margins of safety, thus suggesting a robust joint design. The fabrication methods and testing of each joint were conducted to validate the structural and operational performance needs of the four-bay truss joint.

The objective of the present paper is to summarize aspects of the RI truss bonded joint design, fabrication, and testing that supported the development of a 6.7 meter deployable linear truss structure. Additionally, the paper while provide a brief overview of the entire truss fabrication, assembly, and deployment methodology. A key component of the information presented herein is the identification of the operational requirements of a deployable RI truss and the impact the requirements have on the resulting joint design. Prioritization of these operational truss requirements led to a non-traditional joint design in terms of both desired strength and stiffness. The remainder of this paper provides a description of the 6.7 meter deployable RI truss project and a description of the fabrication and experimental test results for the bonded joint test articles.

2. PROJECT DESCRIPTION

A four-bay, linear RI truss was fabricated and deployed at NASA LaRC in August 2005 to provide further validation of principles demonstrated under the LRA and ISAT programs for truss structures and materials at the component level. The representative full-sized truss, approximately 6.7 meters in total length, was used to demonstrate fabrication issues as well as operational and system performance in an earth environment. Additional performance features of the multi-bay truss simulated truss characteristics required for on-orbit deployment; such as, inflation, tube heating, and precision guidance mechanisms. Photogrammatic and laser-based measurement techniques were used for monitoring and recording critical positions along the length of the truss during the fabrication, stowage, and deployment phases. The four-bay, linear RI truss fabricated at NASA LaRC had a triangular cross-section or footprint as depicted in the center image of Figure 1. The three orange colored tubes aligned in the vertical direction of Figure 1, are typically referred to as longerons when used in space truss applications, and are composed of carbon-fiber reinforced polymer-matrix material. The longerons are the components of the RI truss that are typically heated and folded to stow the truss or heated and inflated to extend the truss. Rigidization of the longerons typically occurs when the tubes cool to a desirable temperature. The longerons are used to join the non-folding portion of the truss structure referred to as the battens. The longerons are typically folded and held between the battens in a stowed configuration. The battens are the thinner of the two tubes in Figure 1, green in color, that are connected to the end-joint perpendicular to the longerons, Since the battens do not bend or deform they remain in a planar configuration, and the entire batten and end-joint assembly is often referred to as a batten plane.

Four primary structural performance requirements were identified for the four-bay, linear RI truss joint. The first requirement is similar to most other structural joint applications, establish a minimum level of axial tension strength. The need for axial tension strength for a RI truss joint stems from the global bending loads applied to the truss structure; both static and dynamic. The maximum axial tension load requirement selected for the four-bay, linear RI truss joint was 1,000 lbf. Torsional loading, the primary loading requirement in all automotive applications, was not considered a significant area of interest for the RI truss joint design since the truss typically experiences very small levels of twist. However, joints that perform well in axial tension generally maintain excellent torsional strength. Secondly, the joint a had to maintain structural integrity after experiencing repeated bending and folding of the carbon-epoxy longeron during required stowing and deployment. During the stowing phase, the longeron undergoes a 90 degree bend with very little radius of curvature. Large curvature imposes severe crimping and bending strains on the longeron in close proximity to the end-joint. An adhesive must have a high strain-to-failure property to maintain a structural bond when subjected to these severe bending loads during stowage. A minimum of 2% strain to failure was selected for potential adhesive candidates. The third requirement was that the adhesive used to fabricate the bonded joint must be room-temperature curable or curable at a slightly elevated temperature due to operational characteristics of the resin material

in the carbon-epoxy RI truss longerons. Finally, the fourth requirement was that the adhesive used to fabricate the truss joint had to maintain good dimensional stability due to thermal and mechanical loading. This last requirement was not investigated in the present study.

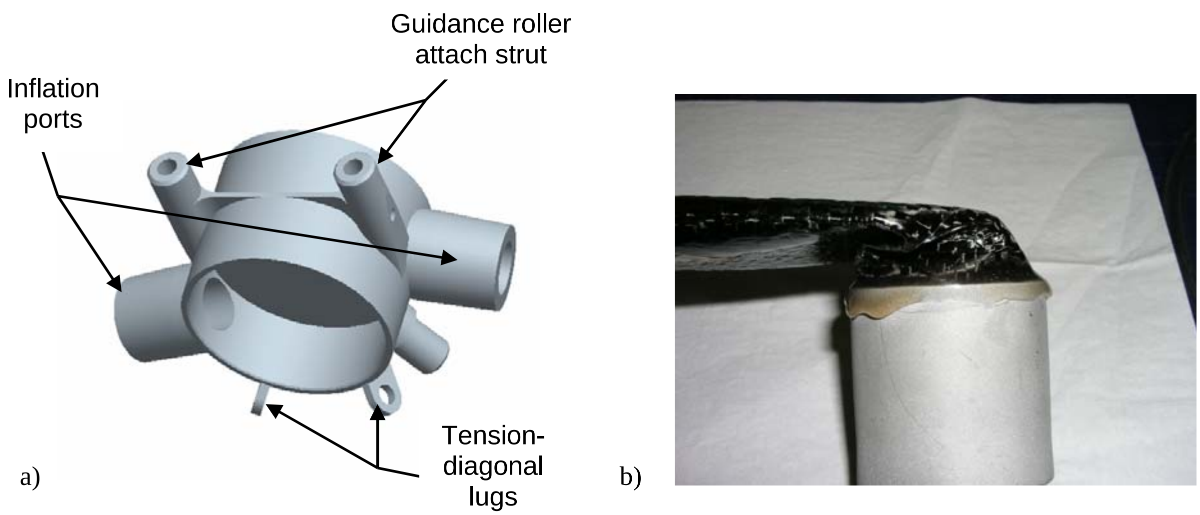


Fig. 2. a) Present four-bay linear truss end-joint design with inflation ports, attach points for guidance rollers, and tension-diagonal lugs shown. b) Test end-joint shown with the RI tube in a stowed configuration.

The joint design for the four-bay, RI truss consists of a 6061-T6 aluminum end-joint that is bonded to a carbon-fiber reinforced polymer-matrix tube, as shown in Figure 1. A more detailed description of the end-joint is given in Figure 2a, and emphasizes the multi-functionality of the end-joint for not only joining truss bays but also providing an entry point for inflating the longerons and guiding the truss deployment. The material on a flight-ready truss end-joint is expected to be either a titanium alloy or a braided/woven carbon-epoxy that would better meet mission requirements for dimensional stability and minimum weight. For this study, an aluminum alloy was chosen for the ground-based testing to meet budgetary constraints. Changing to titanium or carbon-epoxy materials from the current aluminum design would provide minor, if any, risk as both fabrication and machining technology for these materials are state-of-the-art. Additionally, the use of a titanium alloy or polymer material is more desirable as bond strength for these materials is typically higher than aluminum for polyurethane-based adhesives. Due to the low glass-transition temperature of the resin material used in the truss tubes, it was desirable to baseline room-temperature curable adhesives that would not adversely affect the carbon/polymer truss tube's mechanical properties during or after curing.

Table 1. Candidate adhesives for bonding the carbon/epoxy tubes and aluminum end-joints.

Adhesive	*Adhesive Type*	*Manufacturer*
DP 460	Toughened epoxy	3M
Uralane 5773	Polyurethane	Huntsman

One toughened epoxy adhesive and one polyurethane-based adhesive, shown in Table 1, were selected for axial tension and tube folding tests to characterize their performance for the four-bay, RI truss. Toughened epoxy adhesives have the desired surface adhesion as well as lap-shear and peel strengths, but are relatively brittle compared to most other adhesives. Conversely, the polyurethane adhesives have low lap-shear and peel strengths, offer a range of good to excellent surface adhesion, yet they excel in their strain-to-failure performance. Since folding and stowing of the truss longeron members was necessary, the ability of polyurethane adhesives to undergo large deformations while still maintaining a structural bond made them an attractive choice for RI truss joints. An example of the large deformations and severe bending that is often required of RI truss longerons is shown in Figure 2b for a test joint configuration.

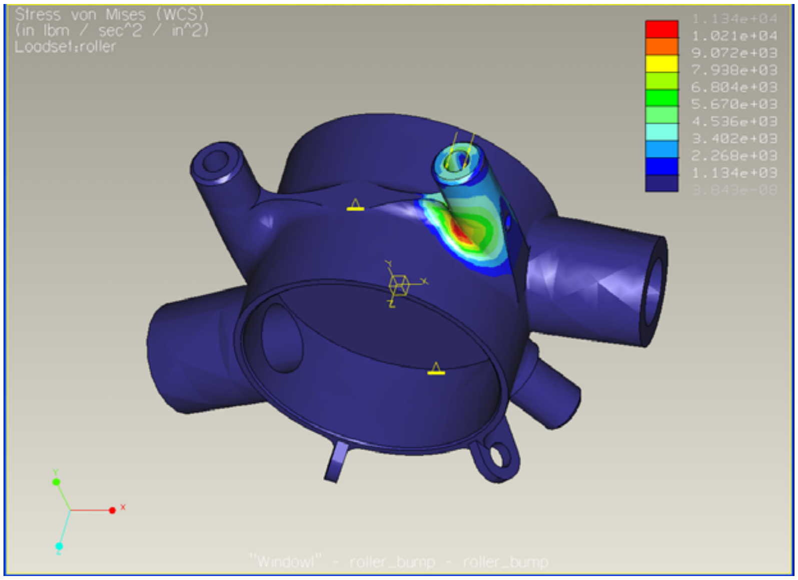


Fig. 3. A contour plot of the von Mises stress results for a linear elastic analysis of the four-bay truss end-joint due to an applied handling load.

3. BONDED JOINT TEST ARTICLE FABRICATION

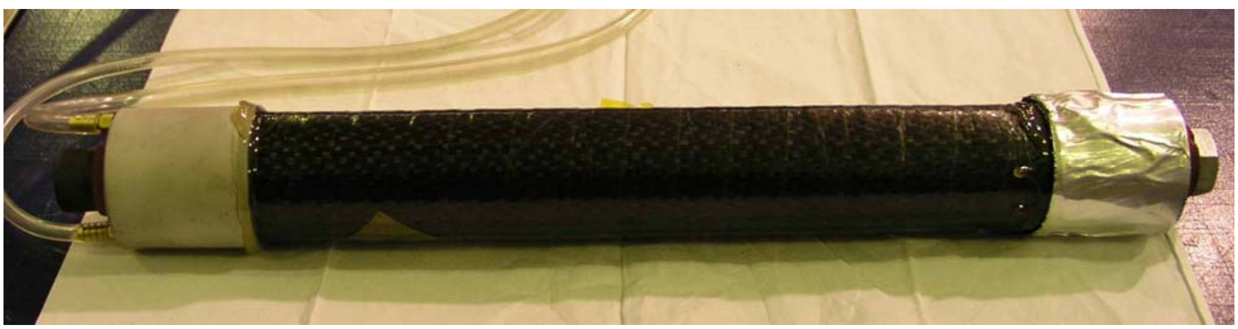
Two different types of joint test configurations were fabricated and tested in the present research investigation. The first type of test joint had two purposes: 1) it was used to qualitatively evaluate the performance of the adhesive bond between the carbon-epoxy tube and the aluminum end-joint, and 2) to determine the change in axial length of the carbon-epoxy tube after it was repeatedly folded and then inflated back to the original, deployed (unfolded) state. An example of the tube folding test article in its stowed and deployed configurations is shown in Figure 4. Only the qualitative results of the bonded joint performance will be reported in the present paper. The second type of test joint was fabricated exclusively to determine the axial tension strength of the prototype joint configurations. An example of an axial tension test article fabricated from DP 460 adhesive is shown in Figure 5 after being tested to failure. The only variation in the fabrication methods used to prepare both types of test articles was bond surface preparation, which was a function of the adhesive type, epoxy versus polyurethane.

The geometry for the end-joints of both the tube folding and axial tension test articles consist of a circular 6061-T6 aluminum tube with a 1.87 inch inside diameter and a 0.125 inch wall thickness. The tubular end-joint is open on one end to accept the carbon-epoxy tube and closed on the other end to maintain pressure during the inflation/re-inflation process. Also, a 0.63 inch diameter circular cutout was placed in each end-joint that covered a portion of the bonding surface along the axial direction of the tube to simulate the inflation port required on the actual end-joint; the cutout is visible in the end-joint shown in Figure 5. The carbon-epoxy tubes have a nominal outside diameter of 1.85 inches and a 0.026 inch wall thickness. The overlap length for the adhesive bondline of both the tube folding and the axial tension test articles is 0.5 inches.

Both types of joint test articles were fabricated in a similar manner and only differed by one significant step depending on the type of adhesive used. Once the aluminum end-joints were fabricated and cleaned, the bonding surface of the end-joint was mechanically abraded using 150-220 grit silicon carbide media in a micro-jet grit blaster with between fifty and seventy psi. of pressure. Next, the carbon-epoxy tube was lightly sanded along the bonding surface using 220 grit sandpaper. Any grit or debris was removed from each bond surface using an isopropyl alcohol rinse. The next step in the fabrication process varied depending on the type of adhesive used. If the DP 460 epoxy-based adhesive was to be

used to bond the tube to the end-joint, a small batch of adhesive was mixed and used to bond the two parts within four hours of the end-joint being grit blasted. If the Uralane 5773 or any other polyurethane based adhesive was being used to bond the tube to the end-joint, then the aluminum end-joint was further prepared using a chemical conversion coating called Safegard 3000 (a product of Sanchem, Inc.). The Safegard 3000 solutions cleaned and chemically etched the bonding surface of the aluminum and left a protective oxide layer. The end-joint and carbon-epoxy tube could then be bonded using the polyurethane-based Uralane 5773. Once treated with the Safegard solution, the parts could be assembled and bonded immediately or weeks later with no significant loss in bond strength. Finally, each joint test article was cured at a slightly elevated temperature according to the manufacturer's specifications, which reduced the cure time from five days for a room-temperature cure to two hours. The elevated cure was only used to accelerate the cure process, and should not provide a distinct advantage over the room-temperature cure properties according to the manufacturer's data.

a)



b)

Fig. 4. A tube (longeron) folding test article shown in the a) stowed and b) deployed configurations.

4. TEST RESULTS AND DISCUSSION

The first type of test articles evaluated were the tube folding test articles, shown in Figure 4. The test procedure for evaluating these specimens was to first heat the test article in a large oven to a selected temperature, fold the end-joints perpendicular to the tube axis, and flatten the tube to simulate a stowed configuration. The test article was then removed from the oven and allowed to rigidize by cooling to ambient conditions. The test article was then placed back in the oven, heated to the selected temperature, and finally inflated to its original deployed state. The previously described procedure represents one full cycle. Each tube folding test article was subjected to a minimum of ten cycles. The qualitative results obtained from visual inspections of the tube folding test articles indicated distinct differences for the two adhesives. The test articles that were bonded using the epoxy based adhesive, DP 460, displayed visible cracking in the adhesive joint at the interface between the carbon-epoxy tube and the adhesive. However, the Uralane

5773 adhesive test articles maintained an unaltered structural bond and never appeared to show any indications of cracking or disbonding from the carbon-epoxy tube or aluminum end-joint.

Fig. 5. A DP 460 axial tension test article shown after being tested to failure.

A total of seven tension test articles were subjected to uniform, quasi-static axial tension at room temperature using a standard tensile testing load frame as shown in Figure 6. Standard data acquisition software was used to record axial displacement and load for each test article. The axial tension failure load results from five of the seven test articles fabricated are given in Figure 7 as a function of adhesive type. The mean axial tension failure load for the DP 460 adhesive was determined from a total of three test articles while the Uralane 5773 failure load was obtained from testing two test articles. The DP 460 provided a mean axial tension failure load of 4,554 lbf., while the Uralane 5773 test articles had a mean value of 2,906 lbf. Therefore, each of the adhesive types easily met the axial tension load requirement of 1,000 lbf. for the truss structure. The quality of the bond was also assessed based on the failure surface for each adhesive test article. The DP 460 displayed an excellent bond to both the carbon-epoxy tube and the aluminum end-joint with all failures being representative of the image shown in Figure 5. In the figure, the DP 460 adhesive is completely bonded to the aluminum end-joint and appears to have stripped the first ply of the carbon-epoxy laminate from the tube. The resulting failure mode was due to the weak interlaminar shear strength of the carbon-epoxy material and is the preferred failure mode for composite bonded joints. The Uralane 5773 tension test articles did not initially provide failure surfaces similar to the DP 460. In Figure 8a, failure surfaces that are representative of the two Uralane 5773 tension test articles are given. The majority of the adhesive remained bonded to the carbon-epoxy tube, but almost completely disbonded from the aluminum end-fitting. This type of failure at the metal to adhesive interface is typically referred to as an adhesive failure and is representative of poor surface preparation. Further investigation into the surface preparation conducted for the aluminum end-fitting revealed that the Safegard 3000 conversion coating was incorrectly applied. Additionally, it was important to validate the performance of the conversion coating for maintaining a suitable oxide layer on the end-joint bond surface as all the end-joints would need to be fabricated and prepared several days before the truss final assembly would occur. Thus, two additional tension test articles were fabricated and tested using the Uralane 5773 adhesive to verify the conversion coating technique and evaluate its capability for providing a quality bond surface after short-term (one week) exposure to lab air.

The two additional tension test articles had the same geometry configuration as the previous five test articles and were fabricated using the Uralane 5773 adhesive, and only differed by changes in their processing parameters. The sixth and

seventh tension test articles were each exposed to lab air, approximately 75°F and 60% relative humidity, for one week after their respective surface treatments of the end-joint bond surfaces were completed. The surface treatment for the sixth test article was grit-blasting alone, using the same grit-blasting parameters previously described, and was fabricated to identify a lower-bound axial tension load for an aluminum end-joint bonded with the Uralane 5773 adhesive to a carbon-epoxy tube. The failure load measured for the sixth tension test article was 2,126 lbf. and resulted in an adhesive failure surface similar in appearance to the one shown in Figure 8a. Thus, the short-term exposure of lab air to the bonding surface on the sixth tension test article resulted in a 27% reduction of the failure load over the previous mean value, and was most likely due to the formation of a weak oxide layer along the bond surface. The seventh tension test article had an aluminum end-joint that was prepared by grit blasting and using the corrected Safegard 3000 conversion coating procedure. After the one week air exposure, the end-joint was bonded to the carbon-epoxy tube using the Uralane 5773 adhesive. The failure load recorded for the seventh tension test article was 3,083 lbf. and provided a joint strength greater than either of the first two tension test articles for the Uralane 5773 adhesive, even after the one week exposure to air. Additionally, the failure surface for the seventh tension test article provided a very good failure surface, shown in Figure 8b, which resembled the failure surfaces obtained from the failed DP 460 adhesive test articles. Thus, the Safegard 3000 conversion coating, when applied correctly to candidate aluminum end-joints, was found to provide an excellent short-term (one week) oxide-layer on the end-joint bond surface that protected the as-prepared surface morphology and resulted in no-loss of axial bond strength.

5. CONCLUSIONS

A summary of the bonded joint design, fabrication, and testing that supported the development of a 6.7 meter deployable linear truss structure was provided. Test results describing qualitative assessments of the bonded RI joint due to folding of the longeron members and quantitative axial strength data were presented. Furthermore, an axial maximum tension load of 1,000 lbf., a 2% strain-to-failure minimum, and the capability of being cured at room-temperature were the project requirements identified for all candidate adhesives evaluated based on the operational requirements of a deployable RI truss. Both the DP 460 epoxy-based adhesive and the Uralane 5773 polyurethane-based adhesive met the project requirements.

The tube folding testing identified the strain-to-failure limitations of the DP 460 adhesive as it clearly began cracking and disbonding at the adhesive and carbon-epoxy tube interface within two or three folding cycles. However, the Uralane 5773 adhesive maintained an unaltered structural bond and never appeared to show any indications of cracking or disbonding from the carbon-epoxy tube or aluminum end-joint. The mean axial failure loads determined for the DP 460 and Uralane 5773 adhesives were 4,554 lbf. and 2,906 lbf., respectively. While each of the adhesives met the operational truss requirements determined for the project, only the Uralane 5773 polyurethane-based adhesive was capable of withstanding the repeated folding cycles without any visual evidence of failure. Thus, the Uralane 5773 adhesive was selected as the adhesive for fabricating the 6.7 meter four-bay, deployable RI linear truss. Additionally, a commercially available chemical conversion coating, Safegard 3000, was identified, applied to candidate aluminum end-joints, and found to provide an excellent short-term (one week) oxide-layer on the end-joint bond surface that protected the as-prepared surface morphology and resulted in no-loss of axial bond strength.

ACKNOWLEDGEMENTS

I would like to thank Wes Lawrence and Judith Watson for their valuable technical discussions that provided additional insight into the applicability of RI truss structures to current science missions and the historical development of deployable RI trusses. I would also like to express my appreciation and gratitude to John Teter for many of the images presented in this paper and Jim Phelps and Eric Lundgren for their participation in the fabrication and testing of the component joint test articles.

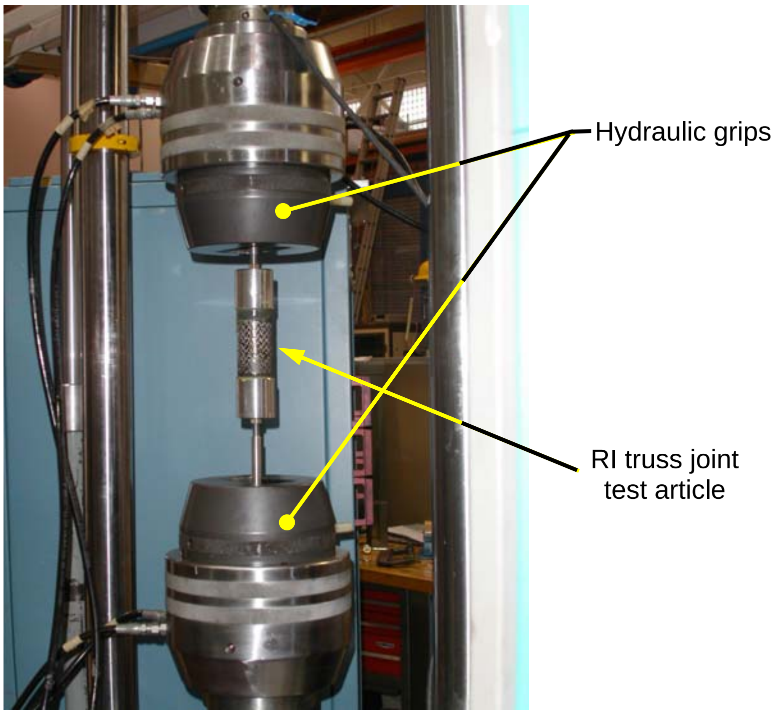


Fig. 6. Test setup for a full-scale, four-bay truss joint test article subjected to axial tension.

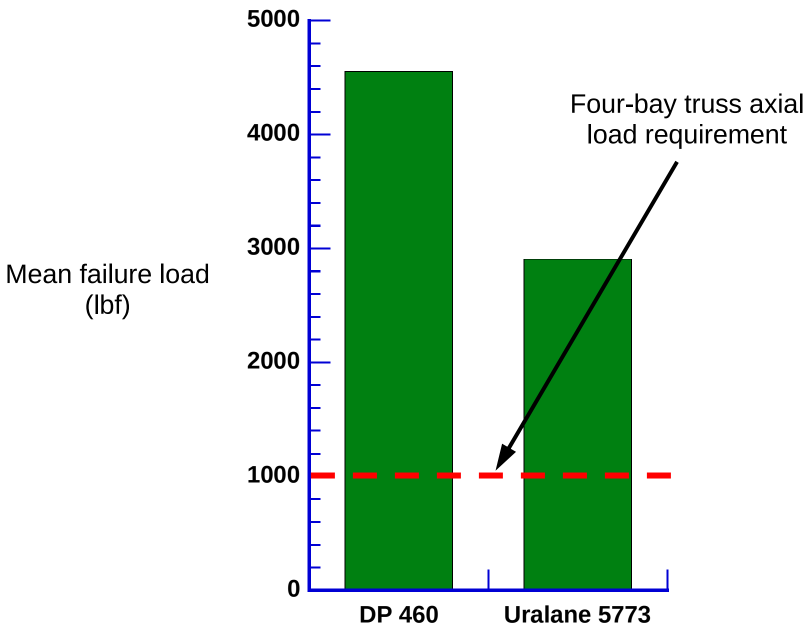


Fig. 7. Mean failure loads for the RI truss joint test articles subjected to axial tension.

a) 

b) 

Fig. 8. Failure surfaces for RI truss joint test articles fabricated with Uralane 5773 adhesive where the conversion coating was a) incorrectly applied and then b) corrected.

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